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(U) COAST GUARD GROTON CT MARINE FIRE AND SAFETY
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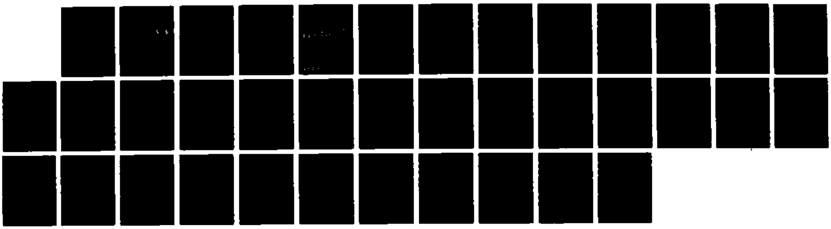

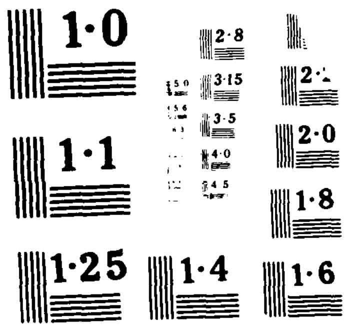
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Report No. CG-M-3-87

AD-A191 032

SURVEY AND EVALUATION OF EXISTING SMOKE MOVEMENT MODELS

BY

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Final Report
NOVEMBER 1987

Document is available to the U.S. public through
The National Technical Information Service,
Springfield, Virginia 22161

United States Coast Guard
Office of Marine Safety, Security,
and Environmental Protection
Washington, DC 20593

NOTICE

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Technical Report Documentation Page

1. Report No. CG-M- 3-87	2. Government Accession No. AD-A191 032	3. Recipient's Catalog No.
4. Title and Subtitle SURVEY AND EVALUATION OF EXISTING SMOKE MOVEMENT MODELS		5. Report Date NOVEMBER 1987
		6. Performing Organization Code
7. Author(s) Robert C. Richards		8. Performing Organization Report No. CG-MFSRS-60
9. Performing Organization Name and Address United States Coast Guard Marine Fire and Safety Research Staff Avery Point Groton, Connecticut 06340-6096		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTCG39-85-A-80196
12. Sponsoring Agency Name and Address Department of Transportation U.S. Coast Guard Office of Engineering and Development Washington, D.C. 20593		13. Type of Report and Period Covered FINAL
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

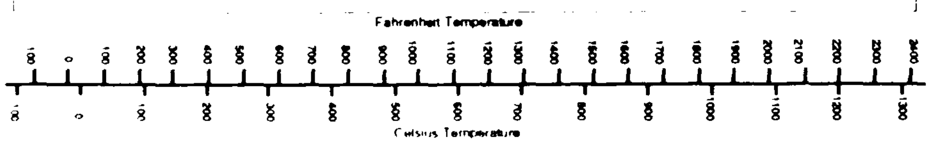
This report provides an independent evaluation of a variety of models which have potential use in describing the movement of smoke. Comparison is made between experimental data from two full-scale fire tests and results from several compartment-zone models. Because of the nature of the models, focus is placed on their ability to predict temperature and the depth of the upper hot gas layer as a function of time. While existing models provide reasonable results for simple compartments, it is clear that dynamic modeling must be extended to regions and situations where a simple two-zone model is not appropriate. The work was done in conjunction with the development of the Smoke Movement Analysis part of the Ship Fire Safety Engineering Method.

17. Key Words smoke, smoke movement, computer models, zone models		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) UNCLASSIFIED	20. SECURITY CLASSIF. (of this page) UNCLASSIFIED	21. No. of Pages	22. Price

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized

Conversions to Metric Measures

When you know (symbol)	Multiply by	To find (symbol)
Length		
inches (in)	2.540	centimeters (cm)
feet (ft)	30.48	centimeters (cm)
feet (ft)	0.3048	meters (m)
Area		
square inches (in²)	6.452	square centimeters (cm²)
square feet (ft²)	929.0	square centimeters (cm²)
square feet (ft²)	0.09290	square meters (m²)
Volume		
fluid ounces, US (fl oz)	29.57	milliliters (ml); cubic centimeters (cm³)
gallons, US liquid (gal)	3.785	liters (l)
cubic feet (ft³)	0.02832	cubic meters (m³)
cubic yards (yd³)	0.7646	cubic meters (m³)
Mass (weight)		
ounces, avoirdupois (oz)	28.35	grams (g)
pounds (lb)	0.4536	kilograms (kg)
Density		
pounds per cubic inch (lb/in³	27.68	grams per cubic centimeter (g/cm³)
pounds per cubic foot (lb/ft³)	16.02	kilograms per cubic meter (kg/m³)
Pressure		
pounds per square inch (psi)	6895	pascals (Pa); newtons per square meter (N/m²)
pounds per square inch (psi)	0.0703	kilograms per square centimeter (kg/cm²)
pounds per square inch (psi)	51.71	millimeters of mercury (mm Hg) at 0°C
pounds per square inch (psi)	0.06895	bars (10⁵ N/m²)
inches of water (in H_2O) at 60°F	1.867	millimeters of mercury (mm Hg) at 0°C
inches of water (in H_2O) at 60°F	248.9	pascals (Pa)
inches of water (in H_2O) at 60°F	0.002489	bars (10⁵ N/m²)
inches of mercury (in Hg) at 32°F	3386	pascals (Pa)
inches of mercury (in Hg) at 32°F	0.03386	bars (10⁵ N/m²)
Energy		
British thermal units (Btu)	1055	joules (J); newton-meter (Nm)
British thermal units (Btu)	0.2520	kilocalories (kcal)
Thermal Conductance		
Btu / hr - ft² - °F	0.0001356	calories / sec - cm² - °C
Btu / hr - ft² - °F	0.4882	calories / hr - cm² - °C
Btu / hr - ft² - °F	0.0005678	watts / cm² - °C
Heat Flow		
Btu / hr - ft²	0.00007535	calories / sec - cm²
Btu / hr - ft²	0.2712	calories / hr -cm²
Btu / hr - ft²	0.0003154	watts / cm²



Conversions from Metric Measures

When you know (symbol)	Multiply by	To find (symbol)
Length		
millimeters (mm)	0.03937	inches (in)
centimeters (cm)	0.3937	inches (in)
meters (m)	39.37	inches (in)
Meters (m)	3.281	feet (ft)
Area		
square centimeters (cm²)	0.1550	square inches (in²)
square centimeters (cm²)	0.001076	square feet (ft²)
square meters (m²)	1550	square inches (in²)
square meters (m²)	10.76	square feet (ft²)
square meters (m²)	1.196	square yards (yd²)
Volume		
milliliters (ml)	0.03381	fluid ounces, US (fl oz)
liters (l)	0.2642	gallons, US liquid (gal)
liters (l)	0.03531	cubic feet (ft³)
cubic centimeters (cm³)	0.06102	cubic inches (in³)
cubic meters (m³)	35.31	cubic feet (ft³)
cubic meters (m³)	1.308	cubic yards (yd³)
Mass (weight)		
grams (g)	0.03527	ounces, avoirdupois (oz)
grams (g)	0.002205	pounds (lb)
kilograms (kg)	2.205	pounds (lb)
Density		
grams per cubic centimeter (g/cm³)	0.03613	pounds per cubic inch (lb/in³
kilograms per cubic meter (kg/m³)	0.06243	pounds per cubic foot (lb/ft³)
Pressure		
pascals (Pa); newtons per sq. meter (N/m²)	0.000145	pounds per square inch (psi)
bars (10⁵ N/m²)	14.50	pounds per square inch (psi)
kilograms per square centimeter (kg /cm²)	14.22	pounds per square inch (psi)
millimeters of mercury (mm Hg) at 0°C	0.01934	pounds per square inch (psi)
millimeters of mercury (mm Hg) at 0°C	0.5357	inches of water (in H_2O) at 60°F
bars (10⁵ N/m²)	401.8	inches of water (in H_2O) at 60°F
pascals (Pa)	0.00402	inches of water (in H_2O) at 60°F
pascals (Pa)	0.000295	inches of mercury (in Hg) at 32°F
bars (10⁵ N/m²)	29.53	inches of mercury (in Hg) at 32°F
Energy		
kilojoules	0.9478	British thermal units (Btu)
kilocalories	3.968	British thermal units (Btu)
Thermal Conductance		
calories / sec - cm² - °C	7373	Btu / hr - ft² - °F
watts / cm² - °C	1761	Btu / hr - ft² - °F
Heat Flow		
calories / sec - cm²	13270	Btu / hr - ft²

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INTRODUCTION

A detailed engineering method is being developed for fire safety design and/or evaluation of buildings (1,2) and ships (3). This method could be used in any or all of the following stages of fire protection:

- Preliminary and final design of ships or buildings
- Fire safety evaluation and redesign of existing ships or buildings
- Fire safety management of operating ships or buildings
- Identification of generic fire safety concerns for a class of ships or type of building
- Identification of generic fire safety concerns for specific ships or buildings

The engineering method involves three major steps. First the identification and definition of the fire safety performance requirements. The next step involves a series of detailed fire safety analyses to determine whether the existing design meets the performance requirements. The final step involves, in cases where the performance requirements have not been met, redesign and analysis until they are. The resultant design will then conform to requirements for life safety, property protection and maintaining a specified level of continuity in operations.

One of the key elements of the detailed fire safety analysis is the determination of the quantity of smoke moved to a particular location, as well as the length of time it takes to get there; in short the extent of smoke movement. This knowledge is important because it has a direct bearing on life safety; it can directly or indirectly affect continuity of operations, and it can have an effect on certain kinds of property which is sometimes hidden for long periods of time.

The work described in this paper was undertaken to provide an independent evaluation of existing fire models. Their strengths and weaknesses were explored, particularly as to their usefulness in providing smoke movement information for the aforementioned engineering method. Improvements to the models which would further this goal were identified.

The mathematical modelling of fire phenomena can be handled in a variety of manners. Stochastic or probabilistic models (4, 5) associate probabilities with all the design features, distribution of combustible material, and human behavior associated with a fire. The flame movement portion of the Engineering Method (4, 5) considers any structure as an assembly of spaces and barriers. Various paths of fire propagation are analyzed in order to determine their probability of success in extinguishing the flame or preventing its spread. In a similar manner, a smoke movement portion of the method is being developed in order to determine the success in maintaining smoke or toxic gas concentrations below critical levels or from spreading to other spaces. Clearly for this methodology to work, however, the determination of such probabilities as passing through a particular barrier requires some deterministic approach. A stochastic approach by itself cannot reasonably yield the details of a fire, such as local temperature and gas concentration profiles which are useful in making engineering judgements in the development of a decision model.

Deterministic approaches can be carried out in three ways: experimentation, field modelling and zone modelling. While experimentation clearly provides a view of the "real situation", instrumentation and burn laboratories are expensive and the complexities of scale modelling are great. Further, the application of burn tests to a different situation requires great insight or some further theoretical understanding of the processes involved. It is clear, however, that burn data are needed to both validate and to provide needed parameters for mathematical models.

Field modelling (6, 7, 8) is certainly attractive from a rigorous scientific point of view. Such models involve the direct solution of the partial differential and algebraic equations which describe combustion and the motion of turbulent flow since most smoke movement is turbulent. Unfortunately, since the present understanding of turbulence is limited, some approximations must be made in order to model the processes involved. Such models involve enormous amounts of computer time and are hence limited to rather small regions of space, e.g. single two-dimensional or axisymmetric rooms. Further, since the models involve the use of experimentally determined coefficients, there is no guarantee that the turbulent model used is physically correct.

These models tend to fall within four broad categories, depending on their treatment of turbulence:

1. Models supported by analytical turbulent theories attempt to account for the non-linear interaction among eddies of different frequencies. These theories have not yet been developed to a state usable for fire modelling.

2. Transport models provide some "engineering" closure for the turbulent transport process. These simulate the gross features of turbulence. Potentially, these are the most useful in fire modelling and include the eddy viscosity concept, mixing-length models, k-ϵ theory (turbulent kinetic energy dissipation) and other ways of modelling the turbulent Reynolds stresses.

3. Sub-grid scale models which divide the turbulent motion into large-scale and small-scale (sub-grid) components. While these are theoretically attractive, the computation time is much too large to be used in engineering applications.

4. Direct numerical simulations involve artifically increasing the Reynolds number until all of the large scale features do not change. Such methods have no inherent assumptions except in their limitations on the Reynolds number. They do require large amounts of computer time and memory and are subject to numerical instabilities.

While such work is necessary to further understand the underlying physics of fire phenomena, an attractive approach to use in engineering design involves zone or compartment modelling. In these models the detailed structure of a fire is ignored; rather the fire region is divided into large zones, such as a fire plume and a hot and cold layer of air. This methodology results in much simpler equations, less computer time and the ability to involve more than one room or compartment. The remainder of this report will discuss several existing zone models. For each model, there will be a discussion of the underlying physics and model assumptions, necessary input, and available input. While several reports have been published providing model comparisons (30,37), the goal of this study is to provide an independent evaluation of exisiting codes from an engineering user's point-of-view. Later a comparison will be made among several of the models for two different fire situations; only those models which are available at Worcester Polytechnic Institute (WPI) have been tested. While all of the codes had to be modified to operate on a DEC 20, this primarily involved input/output routines; none of the models' physics were altered.

Models to be discussed include: ASET, ASET-B, the Harvard code, FAST COMPBRN, Klote, Evers & Waterhouse, BRI, Cal-Tech, Dayton, NBS-I and NBS-II.

The Klote Model

This "smoke control" model is not really a fire model (9), but rather provides the steady state airflows between compartments. It includes stack effects, along with the effects of wind and mechanical ventilation. The temperature profile throughout the building is input to the program; this allows one to look at the effect of a fire but not to predict the fire behavior itself. While one recognizes the use of such results in dealing with cold smoke, the model does not deal with smoke concentration or any fire phenomena.

The Evers and Waterhouse Model

This British model (10) calculates the steady flow movement of air due to the buoyancy generated by a fire, stack effect, wind and mechanical ventilation. The temperature of the rooms above ambient is given by a quasi-empirical relationship; temperatures are not predicted from the basic physics. It is assumed that all such temperatures are stable (the time constant for smoke spread is much greater than for fire growth). It is assumed that smoke diffuses instantly in all compartments except for vertical shafts (where the smoke moves with the airflow) and the corridor outside the fireroom (where a simple analytical model is employed). The model includes the stochastic simulation of doors and windows being opened, ambient wind, and fire breakthroughs. While this model shows promise in dealing with cold smoke, it is not truly predictive based on physical principles; the fire behavior and the spread from the fire region leave much to be desired.

The remaining models are directly applicable to predicting smoke movement. They will be discussed in more detail.

The ASET Model

ASET (11, 12, 15) was designed to determine the Available Safe Egress Time for a simple one-compartment fire. The FORTRAN program was developed at NBS under the direction of L. Cooper. The model itself is extremely simple and, as such, provides minimal information. However, it can be useful as a conservative design tool for simple geometries.

The ASET model, like most zone models, uses several simplifying assumptions. There are three distinct regions within the fire room. The fire is modelled as a buoyant plume; algebraic equations are used to describe the plume rise. The hot gas is carried into an upper gas layer which is always fully mixed (isothermal). A lower layer remains at ambient conditions. As the fire continues to burn, the upper gas layer grows in depth and its temperature changes as well. The model involves the time-dependent solution of a mass and an energy balance for the upper zone.

Vents:

The model is intended for a single compartment. The compartment is sealed, with sufficient leakage of cool air from the floor region to maintain a constant pressure in the room.

Heat Transfer:

No detailed heat transfer calculations are made. Rather the user must provide an estimate of the fraction of the fire's energy generation rate which is lost by radiation from the plume and the combustion region; a value of .35 is typical for flaming fires. One must also supply the fraction lost to the boundaries (wall, floor, ceiling, etc.) of the room; it is suggested that this value varies from .6 (for large ratios of ceiling span to room height, smooth ceilings, and fires away from the walls) to .9 (for opposite conditions). Clearly such a value depends on wall construction and is a time-varying parameter; no understanding of the heat transfer involved can be obtained from this model.

Combustion:

Again, no real model of the combustion process is made. The user must provide some estimate of the energy generation rate as a function of time. It is assumed that there is always enough oxygen in the room to provide these generation rates.

Input:

The model requires the heat loss ratios and the heat generation rate discussed above. The height of the fire base, ceiling height and room area, are also needed.

Output:

The program calculates the upper layer thickness and temperature as functions of time, along with the concentration of any products of combustion whose production rate is known or is related to the heat generation rate. The program also informs the user at what time the values exceed some hazardous criterion as established by the user, e.g. the temperature below eye level has exceeded 240^{o}F.

The ASET-B Model

This (13) is virtually the same model as ASET, except that it was written in BASIC and designed for operation on a PC. It involves a somewhat simpler, albeit less accurate, numerical scheme to solve for the hot gas layer height and temperature. The program does not keep track of products of combustion and does not have the hazard triggers; the latter are certainly not difficult to look for by eye. While the model is still confined to a single room, it is suggested that when the hot layer interface drops to the top of an open door, that the area of the two connected rooms be combined and a second computer run be made. This obviously provides a time gap between the two runs and would have limited value in many situations.

The FAST, NBS, Dayton, Cal-Tech and COMPBRN Models

These models (14, 16, 18) differ only slightly in algorithm; their basic structure and purpose are very similar. Since a working version of FAST is available at WPI, it will be discussed in detail. Again the model consists of two layers or zones and a plume region which transports hot gas into the upper layer. Mass and energy balances are developed for the various zones.

Vents:

The model is designed to handle a number of rooms on the same floor (the newest version can handle multi-stories.) It is assumed that each room has two layers; i.e. the smoke remains warm enough to be driven by the thermal energy of the fire. A vent may be specified between any two rooms or the ambient surroundings. When the hot layer of one room reaches the transom of a vent, the gas moves into the next room; the flow rate depends on the pressure difference between the two rooms caused by the fire.

FAST also includes intraroom mixing between layers as flow proceeds from one room to the next; while little energy is interchanged in this process, smoke can be injected into the lower cold layer. Quintire's research (16) is the basis for the algorithm which incorporates this phenomenon into the model.

Heat Transfer:

The modelling of heat transfer is rather complex. Radiation can leave a layer by going to another layer or to the walls, exit through a vent, heat up an object or change the pyrolysis of the fuel source. All zones and surfaces are treated as grey bodies with constant emissivity. Absorption and emission are considered constant throughout a gas layer. Convection is considered between the gas layers and the walls, the floor and the ceiling. Empirical relationships are used for the film coefficient. Conduction through the walls is necessarily considered, since radiation and convection depend on the surface temperature of the walls. The room is divided into two wall areas, the upper wall area (includes the ceiling) and the lower wall area (includes the floor). Only one-dimensional heat transfer is considered, so that as the gas layer drops further into the room, the wall temperature at the interface changes instantaneously.

Combustion:

The mass pyrolysis rate must be specified as a function of time along with the efficiency of combustion; combustion is not predicted. The fuel properties must be supplied (heat release/mass, fuel makeup and inlet temperature, etc.). Products of combustion can be given as some fraction of the burn rate.

Input:

The program requires the following: room and vent geometry and interconnections, wall properties (single values of conductivity, specific heat, emissivity, and thickness).

Output:

The program provides the upper and lower layer temperatures and the height of the interface for each room, ceiling and floor temperatures, air flowrates and several components of the heat transfer to the two layers. It also, if desired, keeps track of the concentrations of products of combustion.

The Harvard Codes

This rather complex set of computer codes (20, 21, 22) has undergone several modifications since Mark 3 of 1978. The model consists of the usual two-zones plus fire plume; Mark 5, used for this comparision, is restricted to a single room with vents. Mark 5.3 allows for forced ventilation, in which the user specifies the flowrate. Mark 6 does not allow for forced ventilation but is a multi-room model. The main advantage of these models is that they have some combustion phenomena incorporated into them. The fire is spread throughout the room from object to object; the user does not have to supply the heat generation rate. This obviously has a tremendous advantage in its predictive capabilities.

Vents:

The model is limited to a single room with a number of vents to an outside ambient pressure. Flow is calculated using Bernoulli's equation, altered by an experimental flow coefficient which depends somewhat on vent geometry. In general, there are two major modes of flow from a room: 1) the flow is driven by buoyancy due to the temperature difference between two rooms, 2) flow is generated due to a change in the mean pressure in a room due to combustion itself. Complications arise in determining the position of the neutral plane in relation to the interface layer height.

Heat Transfer:

While the radiation modelling is rather complete, it is assumed that the lower wall remains ambient. No correction is made for the area of the vents. Convective heat transfer is included between the hot layer and the upper wall (including the ceiling) and to objects. In order to avoid having the wall temperature vary as a function of height, as the hot layer falls the newly exposed region absorbs enough energy to instantaneously give it the same temperature as the hot wall. To correct for this error, only half that energy is considered removed from the layer. Heat conduction through the wall is obtained using a one-dimensional time-dependent solution. Only the Harvard and Dayton models allow for the calculation of radiation between objects within a room; this is important if one is interested in flashover of multiple combustion sources.

Combustion:

Three types of fires are allowed in the Harvard model: a burner, a pool fire, and a growing fire on a slab (modeled using data taken from a burn experiment using flexible polyurethane foam). The burner model is the simplest; the fuel burning rate is specified and is independent of conditions within the room. In the pool model, the burning area remains constant over a circular pool. The heat received by the fuel by convection and radiation from the flames, upper walls and ceiling and from the hot gas layer vaporizes (pyrolizes) the fuel. Hence the pyrolysis rate from the pool varies with the time-dependent conditions of the room. In the growing fire, the initial ignition is over some user-determined small area, but the heat transfer to the fuel source causes the fire to grow or dissipate. The growth is determined from a semi-empirical formula based on open-air burning tests; the growth neglects the early power law and assumes a radius which grows exponentially with time. The efficiency of combustion is assumed (.65 for polyurethane foam) as is the fraction of the heat released which emerges as radiation (.43). Such a fire responds to low levels of oxygen by reducing the burning rate.

Input:

The following are the major variables required to use the model: room geometry including vents, ambient conditions, objects within the room (combustible or not) along with their heat transfer and combustion properties, wall thickness and its heat transfer properties, flow coefficient for vents and heat transfer coefficients for the air.

Output:

Concentrations of oxygen, CO, CO_2, water and smoke are calculated from empirical small-scale tests. Depth and temperature of each layer, various energy fluxes (e.g. to each object, through each vent), burn rate, depth of the hot layer, surface temperatures of objects, walls, flames, and hot layer, and the mass of objects are determined as functions of time.

The BRI Model

From the point of view of smoke movement, this is the most ambitious of the models to be reviewed here. It (23) attempts completeness in many areas, but suffers from its lack of a truly predictive combustion model. Its basic structure is the same as the other models, except that it is a multi-compartment, multi-floor model. Each compartment consists of a hot and cold gas layer with plumes carrying hot gases from the fire to the upper layer.

Vents:

This model is the most systematic in accounting for the various flow regimes between rooms. The flow between rooms is driven by the hydrostatic pressure differences. This is the only model which allows for "choked flow" which occurs when the hot layer becomes very thick; the entirety of the return flow from the neighboring cold layer may not be able to penetrate the upper layer. The model does not include the intraroom mixing of FAST. The model allows for the interconnection of rooms on multiple levels; however, Tanaka clearly states that the weakest point of the model is the treatment of the transport of gases in vertical shafts. The program also treats the variation in the outdoor pressure due to wind. Tanaka reports on preliminary work on the movement of smoke in highrise buildings, but substantial refinements are needed, such as the inclusion of forced ventilation.

Heat Transfer:

The treatment of radiation is somewhat simplified, since it ignores radiation through vents and does not directly include radiation from the fire source. Convection is modelled in the upper layer only; heat transfer of all types between the lower layer and the lower wall is ignored. The wall is modelled using the standard one-dimensional time-dependent conduction equation.

Combustion:

This model allows only for the inclusion of a single fuel source. Fuel input is not predicted in the context of the local time-dependent conditions, but rather the user must supply the mass loss rate. No real coupling exists between fuel input and thermal conditions. However, not all of the fuel input is necessarily combusted in the source room; as it is pyrolized, the gasified unburnt fuel may be transported to other rooms. The model does look at the actual stochiometric combustion process and corrects for incomplete burning. Two basic algorithms are developed to account for control of the burn rate based on levels of oxygen content in the air. Since some combustion chemistry is accounted for, mass balances for oxygen, CO_2, CO, and nitrogen are included.

Input:

Input consists of building and vent geometry, including vertical shafts between compartments; thermal properties of the floor and ceiling, (which includes the walls) and combustion properties of the fuel, including an empirical value for the fraction of the fuel turning to soot or char. The major requirement is the specification of the pyrolysis rate; in effect this makes this suitable for gas burner studies.

Output:

Model output includes the upper layer temperatures and interface height in each room, various mass and energy fluxes between rooms, and the concentration of gases and combustion products described above.

FULL-SCALE EXPERIMENTS USED FOR COMPARISION

Comparisons were made between model results and experimental measurements for two different burns. The Nike test (24) was carried out by the National Bureau of Standards in a burn room and an attached corridor with a small floor vent. While a variety of experiments were performed, the data used here for comparison were for a room with dimensions of 3.3 x 4.3 x 2.3 m, while the corridor was 2.4 x 20.2 x 2.3 m. The two were connected by a door with a width of 1.07 m and a 2 m height. An opening .95 m wide x .15 m high was located near the floor of the corridor and vented to the ambient environment; all other cracks were sealed. A 100 kw .3 x .3 m methane diffusion burner was placed .24 m off the floor in the center of the burn room. ZnCl was introduced as a smoke bomb to simulate the transport of smoke. Measurements were made using thermocouples and photometers, while visual recordings of the smoke height were also made. The thermocouples indicated that the temperature in each layer was not uniform, so that a difference of 10, 15, or 20% from the uppermost thermocouple reading was used to establish the interface of the hot and cold layers; an average of the 10% and 20% readings were used for this comparison. Photometers also indicated a variation in smoke density within each layer and were in general agreement with the temperature measurements. Visual observations typically indicated an upper layer thickness less than that measured with thermocouples. A comparison of the data with results from several computer models has been published by Jones and Quintiere (26).

For the second experiment (25), data were taken from a ship lounge burn carried out aboard the T/V A.E. Watts. The lounge measured 7.11 x 5.3 x 2.0 m and was outfitted with a typical combustible fuel load (approximately 8650 kBTU). While several tests were carried out, comparisons were made only for a burn which involved passive ventilation (test #3). Two overhead terminals were ducted together and open to the atmosphere; these had a minimum cross-sectional area of 2.1 square feet. Since most of the computer models make no attempt to handle vertical vents, approximately 4 square feet was added to the door area (1.5 square feet being the Coast Guard approximation of any cracks and leaks). Three photometers and an array of thermocouples were used to monitor the fire growth. The fire was started using a wastepaper basket containing 5 quart-size milk cartons and 2 oz. of naptha. The basket was placed near the back of the cushion of a sofa; the weights of the sofa and a nearby chair were monitored during the burn. In less than 10 minutes, it appears that the sofa was reduced to ash. The chair also burned rapidly, but apparently did not ignite until the sofa was completely burned. The data for the first 10 minutes involving primarily the wastebasket and sofa (pre-flashover phase) were used for comparison.

MODEL COMPARISON

Most of the computer models require the fire's heat release rate as input. For the Nike burn this is simple, since the fuel rate of the diffusion burner was fixed at 100 Kw. Figure 1 indicates an estimate of the heat release rate for the Coast Guard burn. This is based largely on the measured sofa mass loss, with the initial rate accounting only for the wastebasket fire. The rate seems to agree reasonably well with energy balances for the room.

Figure 2 shows a comparison between results from the ASET model and the Nike burn. Since the ASET model handles only single compartments, the dimensions of the room and corridor were combined into a single room. The two easiest variables to analyze are the height of the upper hot gas layer and its temperature; both are determined as a function of time. While these are not clear representations of "smoke", it is obvious that the speed at which the upper layer descends determines the time available for escape before visibility is impaired or negated. In order to determine the sensitivity of the model to the user-specified heat loss ratio, this ratio was varied from .6 to .9. The results clearly indicate a large disparity among predicted temperatures, depending on the choice of the heat loss ratio. From Cooper's suggestions, the heat loss ratio for this burn should be around .9; a value of .8 causes good agreement with the temperature results. However, the layer height prediction indicates a much lower value of heat loss. This discrepancy may be a function of the experimental measurements. For example, over the first 150 seconds or so, visual observations (not shown) indicate layer heights greater than the model predictions. Two major points are clear from the ASET results: 1) the temperature results require a good estimate of the heat loss; if one were interested in accurate temperature predictions, another

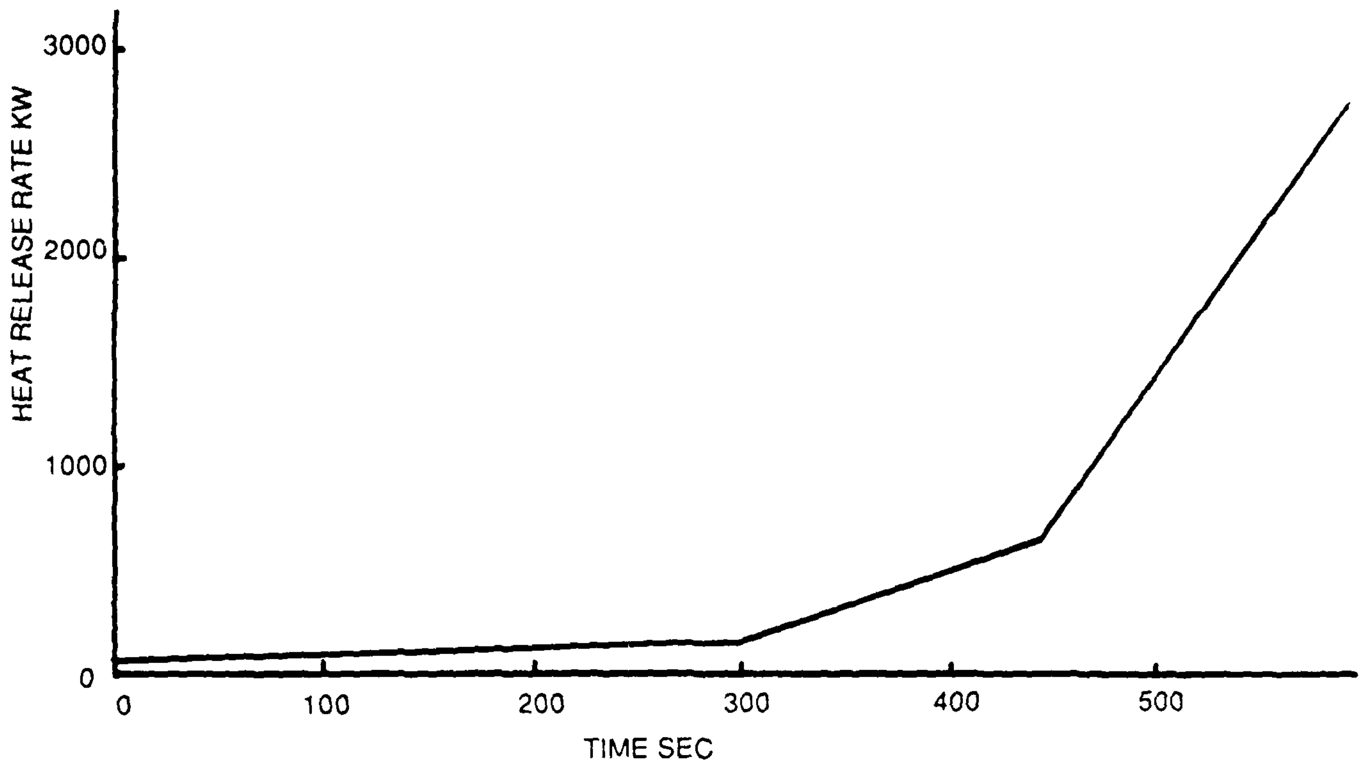

FIGURE 1. HEAT RELEASE RATE USED AS INPUT FOR USCG LOUNGE BURN

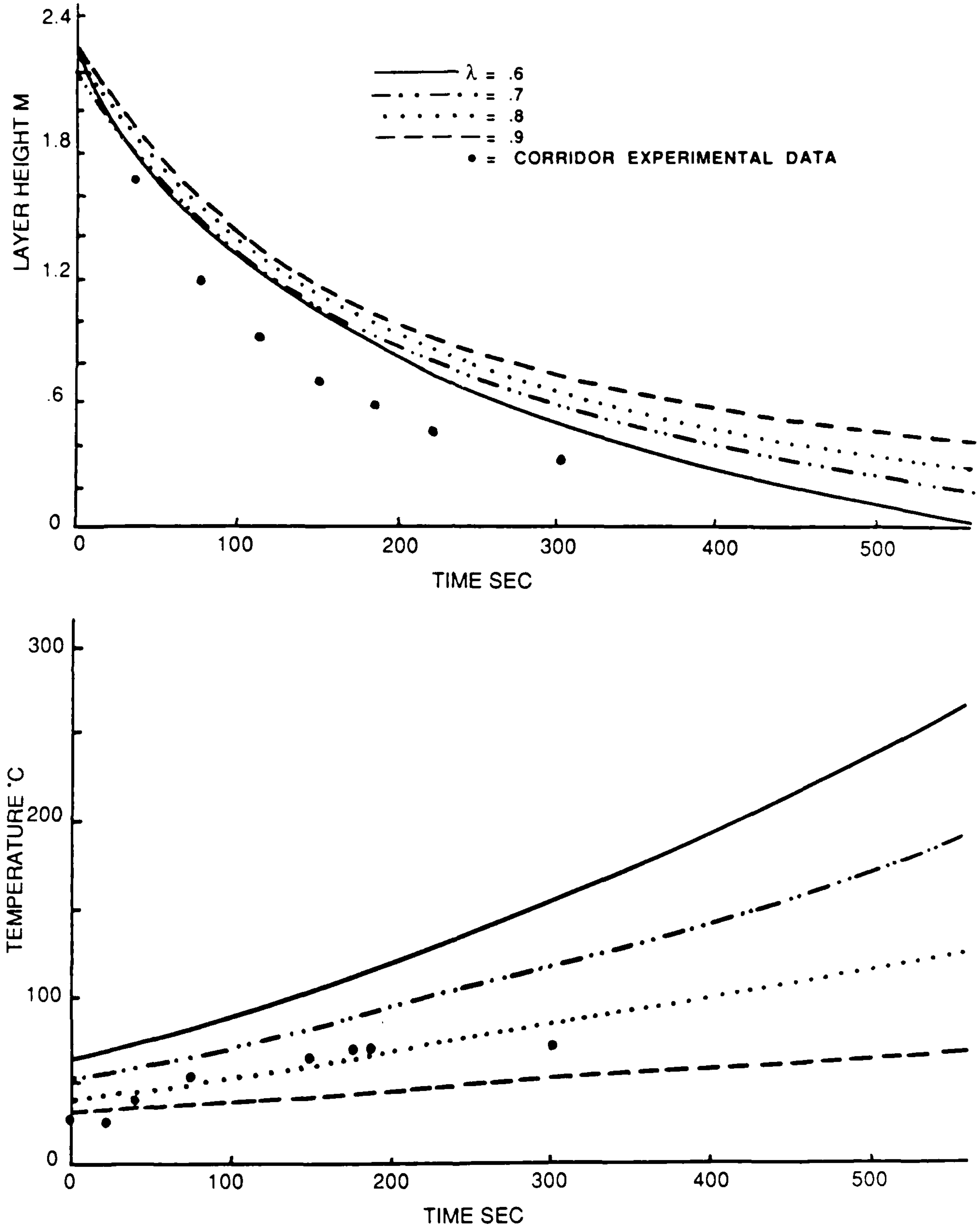

FIGURE 2. RESULTS FROM ASET FOR THE NIKE BURN ROOM PLUS CORRIDOR.
The heat loss ratio, λ, is varied from .6 to .9

model might be in order. 2) The layer height predictions are not as sensitive to heat loss. The "safe egress time" based on layer height does not vary greatly.

Figure 3 shows similar comparisons with the Coast Guard study; for the Coast Guard burn, only the burn room dimensions were used. To show the relative insensitivity of the predicted layer height to heat loss, the ratio was varied from 0 (insulated) to .9. In this case the .9 yields good agreement with both layer height and temperature. Clearly the insulated room model yields absurdly high temperatures; since the model does not respond to combustion conditions, virtually infinite temperatures (computer overflow) can be obtained. In contrast, the time for the hot smokey layer to completely reach the floor only varies by a factor of two.

In Figure 4, results for the Nike burn are compared with the FAST model. Since this model allows for several compartments, the room and corridor were treated separately. Reasonable estimates were made of the wall properties based on the discussion in the NBS report. In general the temperature predictions were quite good, although the "FAST" temperature always rose too quickly. This is likely due to the assumption of two layers, even at the onset of the fire. Clearly when the fire starts, it is impossible to think of a distinct two layer system. It is also unlikely that the fire instantly attains a heat release rate of 100 Kw. The prediction of the layer height in the corridor is quite good. In the burn room, the layer drops too quickly early in the fire, but then it tapers off and reaches the floor too slowly.

Figure 5 shows comparison with the Coast Guard burn. The sophistication of the model certainly does not yield better results than the simple ASET model. The predicted temperature is too high and the layer height does not drop. It is unlikely that this is due to mis-selection of wall properties, since the errors in layer height and in temperature indicate opposite changes in heat loss. One possible suggestion is that the plume model does not entrain enough cool air into the upper layer; this would cause the energy in

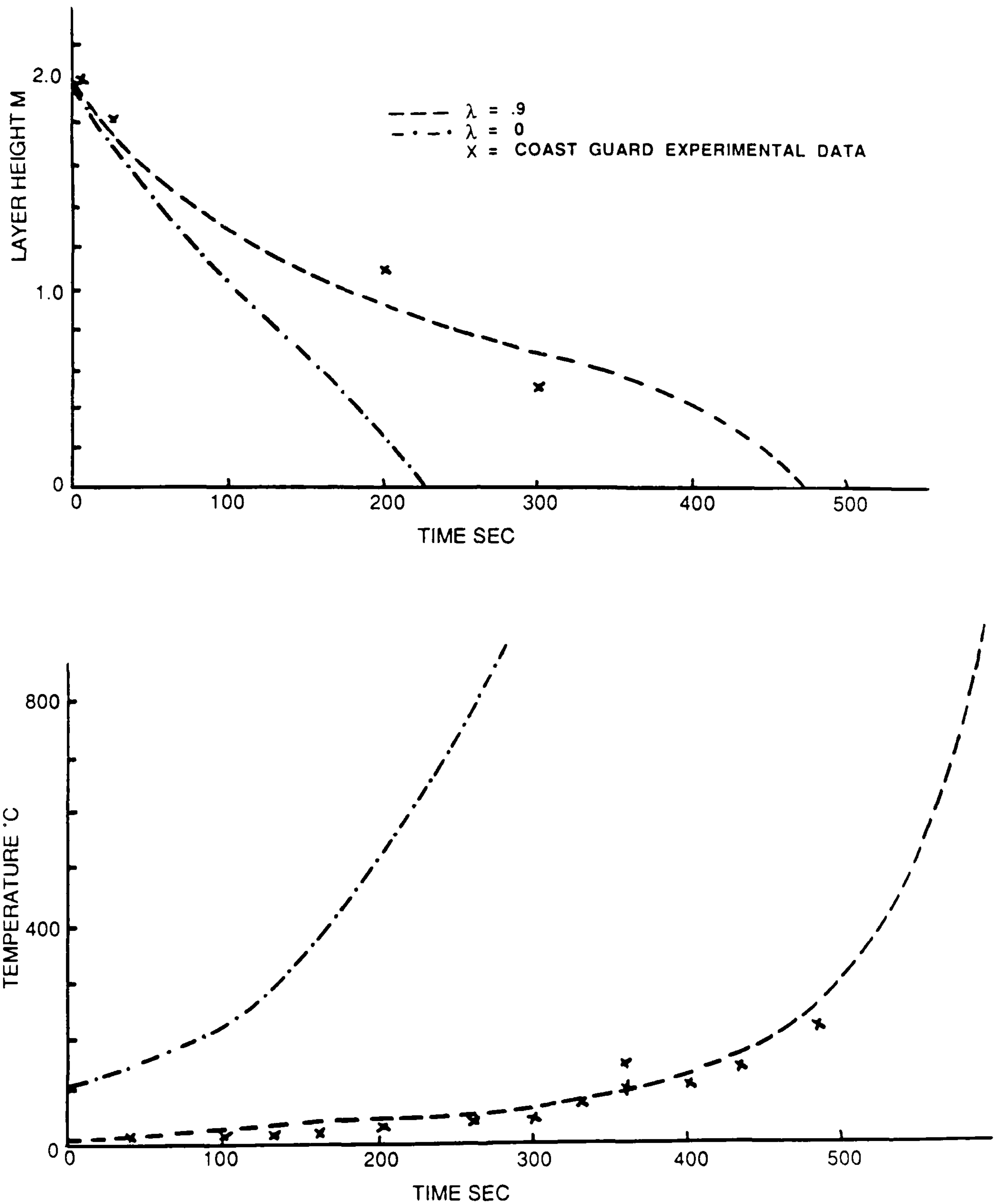

FIGURE 3. RESULTS FROM ASET FOR THE COAST GUARD BURN.
The heat loss ratio, λ, is varied from 0 to .9

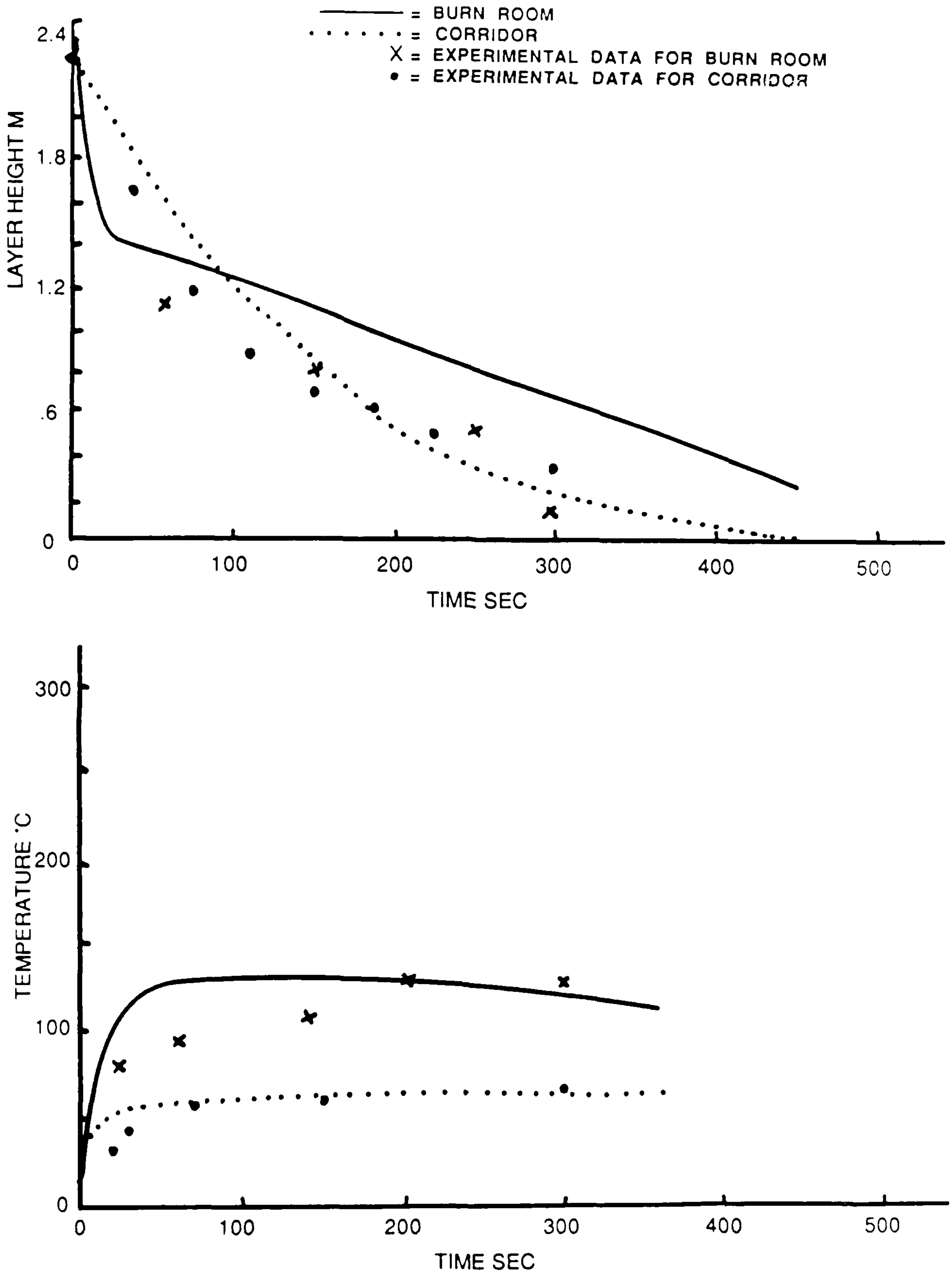

FIGURE 4. RESULTS FROM FAST FOR THE NIKE BURN

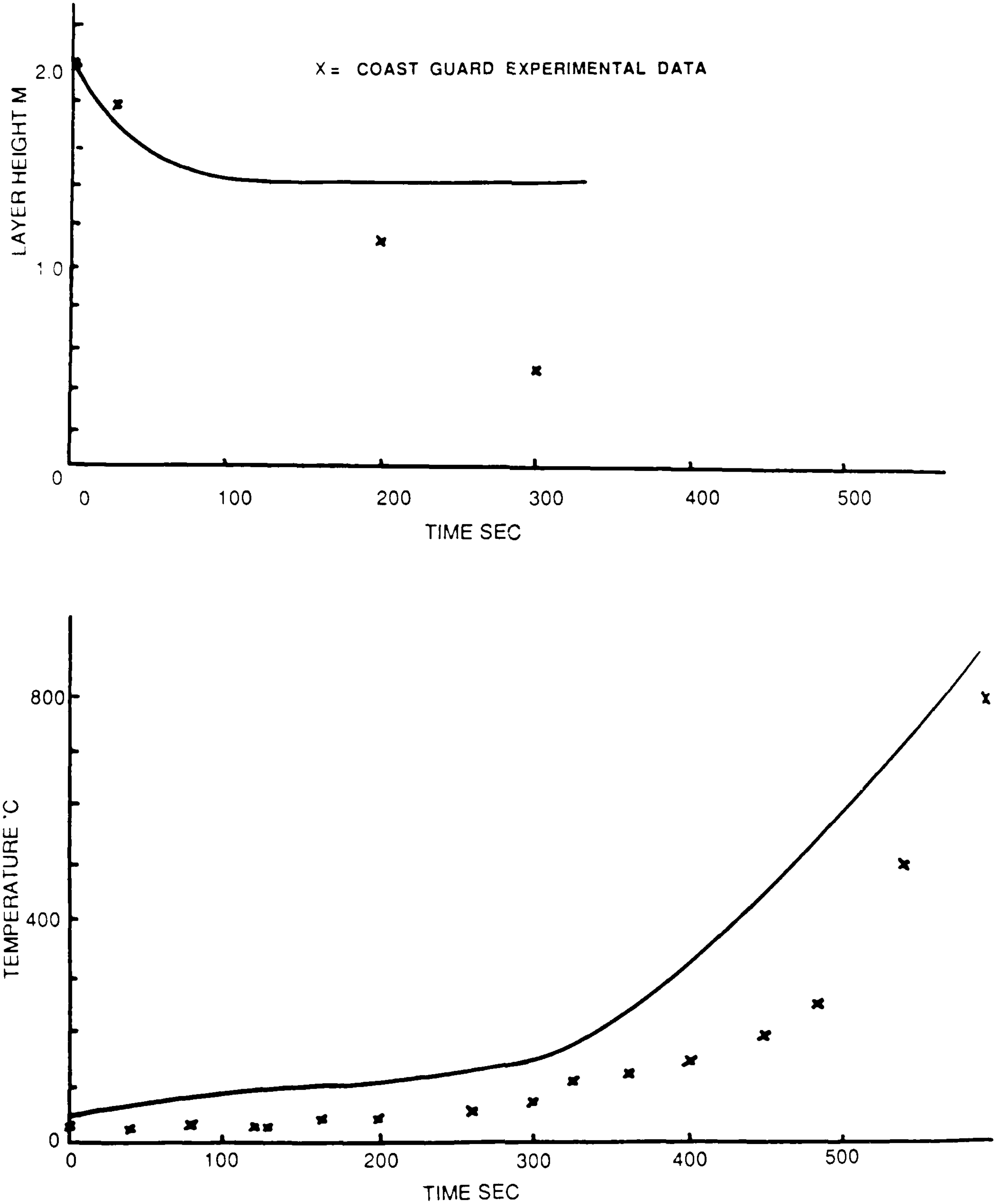

FIGURE 5. RESULTS FROM FAST FOR THE COAST GUARD BURN

the upper layer to be spread out over more volume (lower temperature and deeper layer). Another more likely possibility arises from the treatment of the corridor. The corridor has been treated not as a separate room but rather as an ambient pressure region (burn room venting to the outside). This causes too great a loss of hot gas from the room with the influx of too much cold air. In contrast, ASET provides for no loss of hot gas; hence the heat loss ratio must incorporate the transport of gas through vents.

Figure 6 shows calculated values of the air flow rate into and out of the room. Both curves indicate wild fluctuations in the flowrates. Empirical doorway velocities were determined only along the vertical center line of the door; estimations of the flowrates in and out appear much larger than those predicted. Both the model and empirical data indicate that up to three neutral planes can exist in the doorway vent.

Figure 7 shows results from the Harvard code, which is designed as a single compartment model with vents. The same wall properties were used here as in FAST. Since this model does not handle multiple compartments, two cases were solved: one which treated just the geometry of the burn room and the other which included the size of the room plus corridor lumped into a single room, as in ASET. As with the other models, the initial temperature rise is much too rapid, but the general prediction is reasonable. In this case, neither geometry yielded good layer predictions. This is likely due to the same reasons discussed for FAST.

The Coast Guard results as seen in Figure 8 are similar. Since the Harvard model allows for some combustion modeling, three fire scenarios were used. The gas burner model used the same heat release rate as shown in Figure 1; as with the other models, this yielded temperatures too high. The polyurethane (PU) growth scenario is based on a subroutine built into the model which uses experimental fire data for a polyurethane foam fire. The temperatures predicted here are initially very good, but then the fire gets too hot and begins to run out of fuel and oxygen. A quite realistic scenario

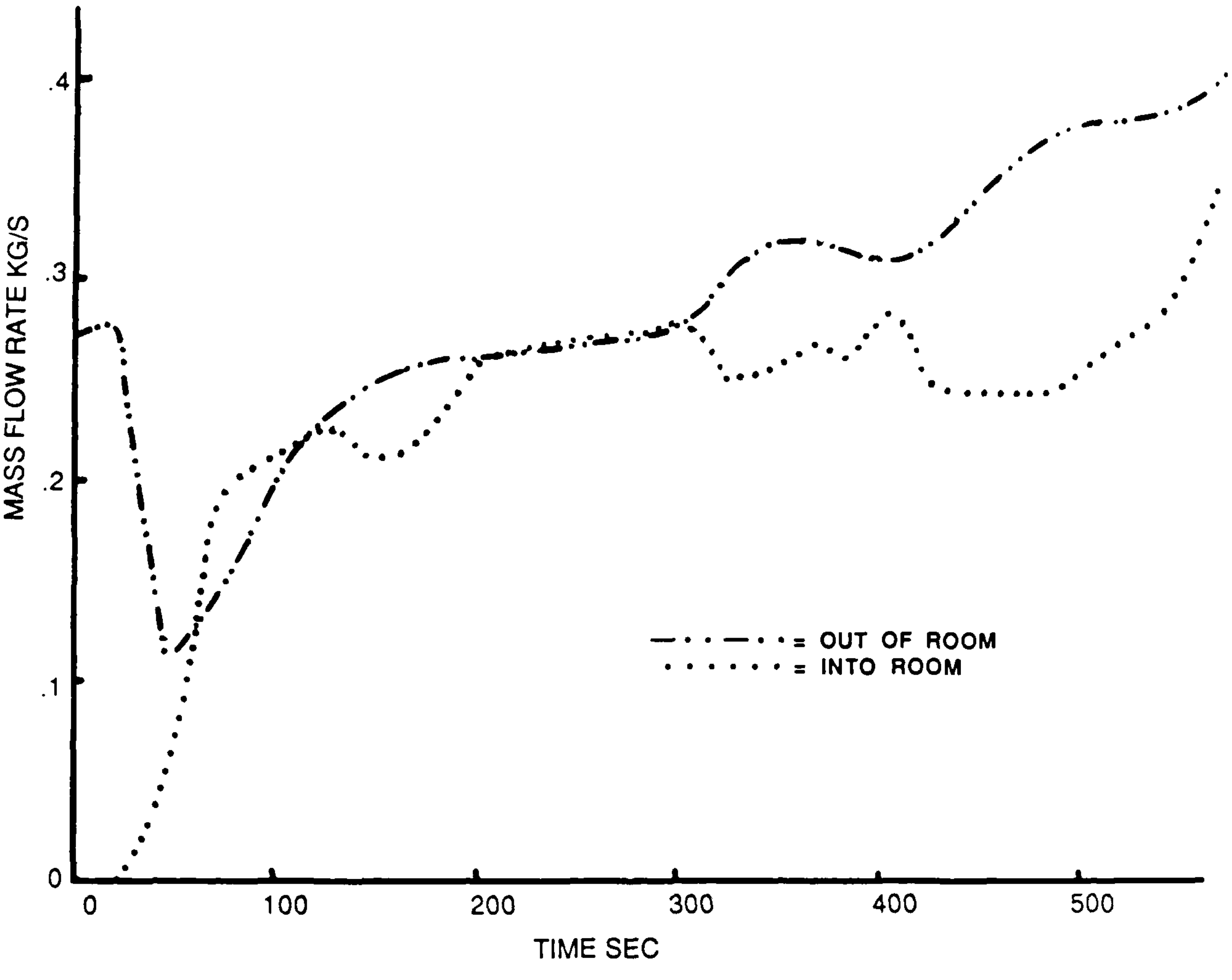

FIGURE 6. AIR FLOW RATES PREDICTED BY FAST FOR THE COAST GUARD BURN

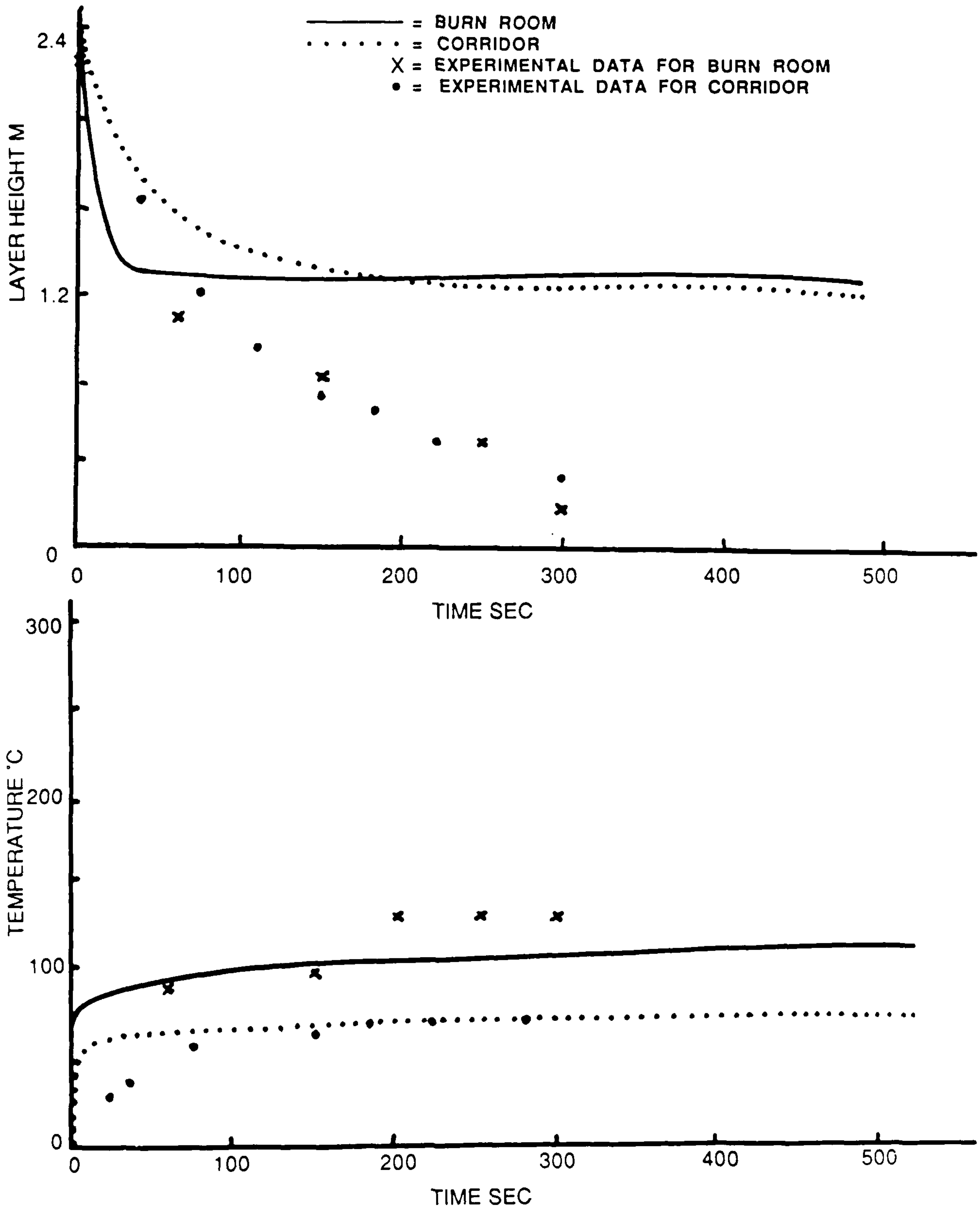

FIGURE 7. RESULTS FROM THE HARVARD MODEL FOR THE NIKE BURN

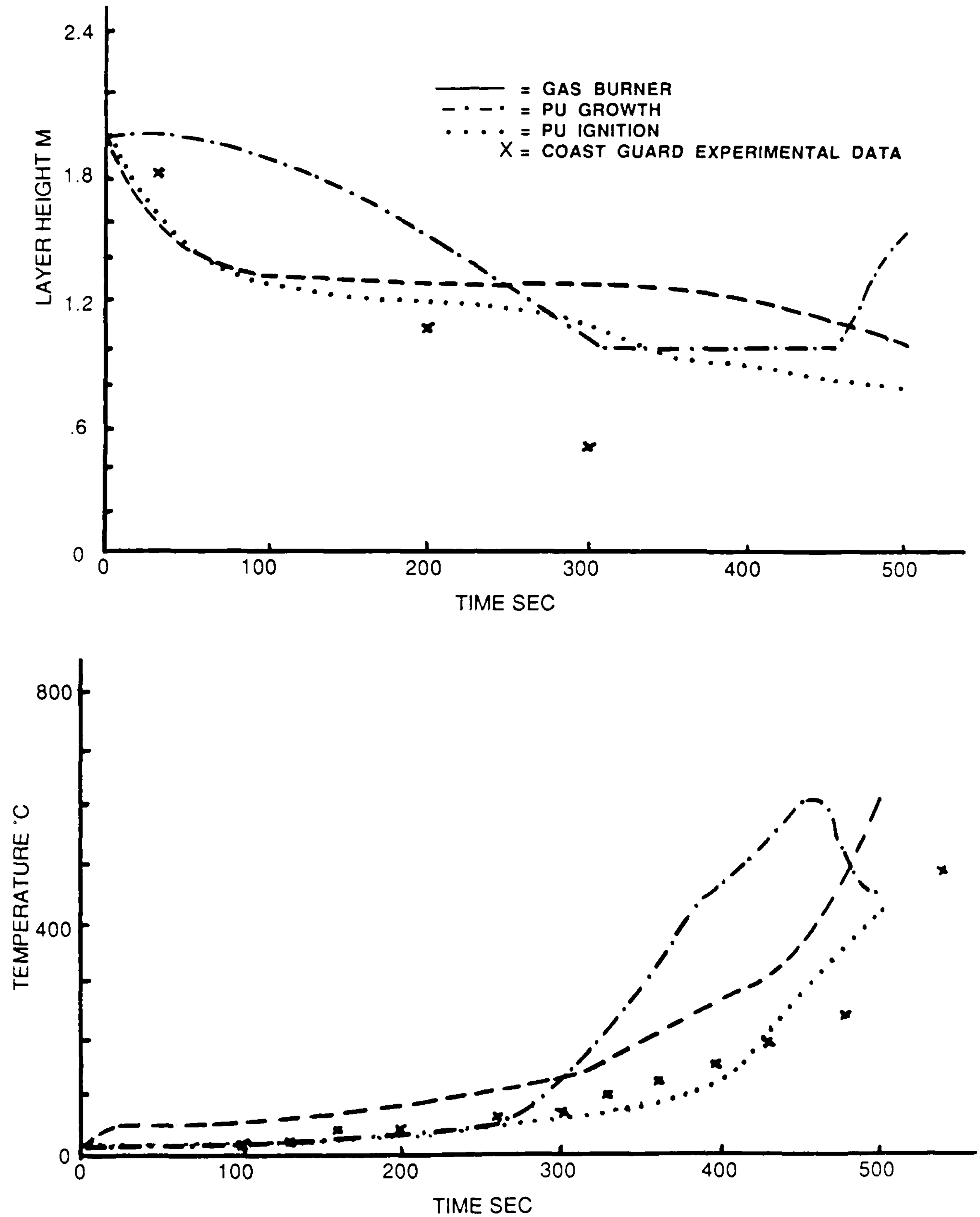

FIGURE 8. RESULTS FROM THE HARVARD MODEL FOR THE COAST GUARD BURN.
Descriptions of the various model scenarios are discussed in the text.

(PU ignition) employs two objects in the room, both PU foam. The first represents the wastebasket with its milk carton fuel load; the second represents the sofa. Initially, the small piece of foam is considered to be burning, the sofa is not. The model predicts the spread of the combustion to the larger PU foam; this time lag seems to produce a heat release rate more in line with that of the real fire. However, the hot layer still does not fall toward the floor.

In Figure 9 comparison is made with the Tanaka model. Since the physics are very similar, its results are also quite similar to those of FAST. Not shown are the Coast Guard burn results which again appear similar to those of FAST. While not pertinent to these simpler cases, since the BRI model does not deal with cold smoke, the model results appear unreasonable or unstable when predicting conditions far from the fire source.

DISCUSSION

In concept, all of these models are fairly similar. However, their complexity varies tremendously from the single leaky compartment of ASET to the multi-floor BRI model. None of them deal realistically with the transport of smoke, except in computing a mass concentration as the smoke is transported from room to room (if the model is multi-room). A second major weakness exists in the consideration of cold smoke. All of the models consider each room to have two layers; this is not reasonable far from the fire source (most references indicate that the assumption is valid only 3-4 rooms away, depending on the fire and room size). Further experimental data are needed to determine the realism in assuming the distance away from the fire before the smoke may be considered cold. One possible modelling technique is to compare the air velocity caused by the fire and that due to other modes of transport (stack effect, HVAC, etc.). When the latter effects overshadow that of the fire, the room should be considered to have uniform temperature and smoke concentration.

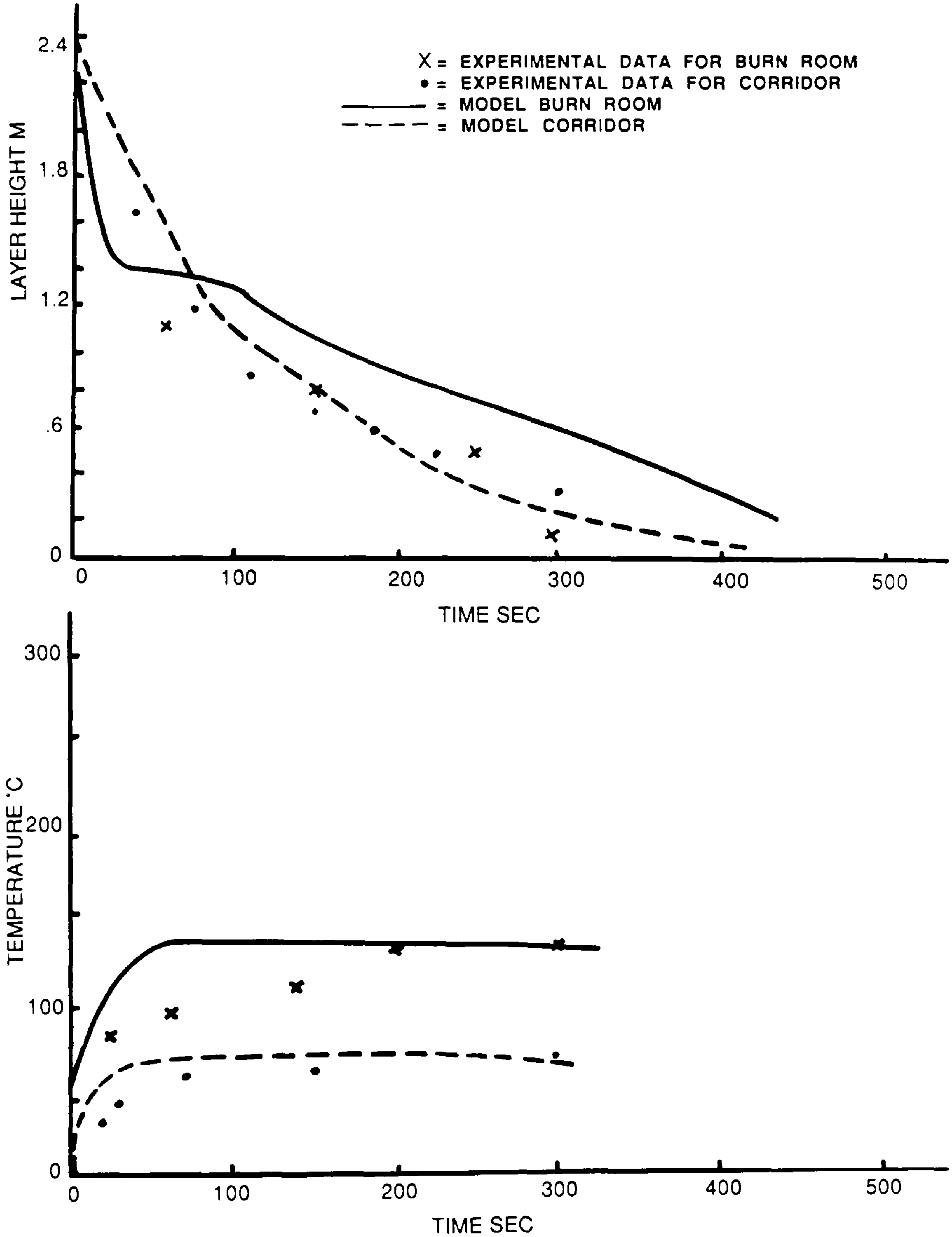

FIGURE 9. RESULTS FROM THE BRI MODEL FOR THE NIKE BURN

Another area of modelling which needs development deals with the problem of obscuration as a function of smoke concentration and particle size. Further, it is known that the smoke ages as it cools and that desposition may occur on walls and ceilings. The elementary physics of these processes are reasonably well understood, but the complexity of the coupling between thermal and gas/particle transport may prevent its inclusion in any model for some time to come.

At present none of the existing models includes enough smoke transport to provide the needed data for the complete development of an Engineering Method for smoke movement in a large network. However, it appears that a combination of existing algorithms would go a long way in fulfilling that need.

REFERENCES

1. Fitzgerald, Robert W., "An Engineering Method for Building Firesafety Analysis", Fire Safety Journal 9 (1985), pp. 233-243.

2. Fitzgerald, Robert W., "The Anatomy of Building Firesafety", Preliminary Draft, Worcester Polytechnic Institute, 1982.

3. Richards, Robert C., "Development of a Ship Fire Safety Engineering Method", U.S. Coast Guard (Project No. 753308.26), August 1985.

4. Ramachandran G., "CIB Workshop on Mathematical Modelling of Fire Growth", Paris, 1981.

5. Ramachandran G., J. of Fire Safety, V. 2, 1979/80, p. 125.

6. Kumar, S., "Mathematical Modelling of Natural Convection in Fire -- A State of the Art Review of the Field Modelling of Variable Density Turbulent Flow", Fire and Materials, 1983, V. 7:1, pp. 1-24.

7. Bos, W.G., VanDen Elsen, T., Hoogendoorn, C.J., and Test, F.L., "Numerical Study of Stratification of a Smoke Layer", Combustion Science and Technology, 1984, V. 38, pp. 227-243.

8. Baum, H.R., Rehm, R.R., and Mulholland, G.W., "Prediction of Heat and Smoke Movement in Enclosure Fires", Fire Safety Journal, 1983, V. 6, pp. 193-21.

9. Klote, J. and J. Fothergeil, Jr., "Design of Smoke Control Systems for Buildings", U.S. Department of Commerce, NBS Handbook 141, 1983.

10. Evers, E., and Waterhouse, A., "A Computer Model for Analyzing Smoke Movement in Buildings", Building Research Establishment, Fire Research Station, Borehamwood, Hertfordshire, WD6 2BL CP69/78, 1978.

11. Cooper, Leonard Y., "A Mathematical Model for Estimating Available Safe Egress Time in Fires", Fire and Materials, 1982, V. 6: 3&4, pp. 135-144.

12. Cooper, L. and D. Stroup, "Calculating Available Safe Egress Time (ASET) - A Computer Program and User's Guide", U.S. Department of Commerce, NBSIR 82-2578, 1982.

13. Walton, W. "ASET-B A Room Fire Program for Personal Computers", U.S. Department of Commerce, NBSIR 85-3144, 1985.

14. Quintiere, J.G., and McCaffrey, B.J., "The Burning of Wood and Plastic Cribs in an Enclosure", U.S. Department of Commerce, V.I., NBSIR 80-2054, 1980.

15. Cooper, L.Y., "Estimating Safe Available Egress Time from Fires", U.S. Department of Commerce, NBSIR 80-2172, 1981.

16. Jones, W., "A Model for the Transport of Fire, Smoke, and Toxic Gases (FAST)", U.S. Department of Commerce, NBSIR 84-2934, 1984.

17. McArthur, C.D., "Dayton Aircraft Cabin Fire: Model Version 3", V.I and II, University of Dayton Research Institute, 1981.

18. Zukoski E.E. and Kubota, Toshi, "Two-layer Modeling of Smoke Movement in Building Fires", Fire and Materials, 1980, V. 4:1, pp. 17-27.

19. Quintiere, J.G., Steckler, K., and McCaffrey, B.J., "A Model to Predict the Conditions in a Room Subject to Crib Fires", CIB Workshop on Mathematical Modelling of Fire Growth, Paris, 1981.

20. Mitler, Henri E., "Zone Modeling of Forced Ventilation Fires", Combustion Science and Technology, V. 39, 1984, pp. 83-106.

21. Emmons, H.W., Mitler, H.E. and Trefethen, L.N., "Computer Fire Code III", Home Fire Project Technical Report No. 25, January 1978.

22. Mitler, H.E. and Emmons, H.W., "Documentation for CFC V", The Fifth Harvard Computer Fire Code, Home Fire Project Tech. Rep. #45, Harvard University, 1981.

23. Tanaka, T., "A Model of Multiroom Fire Spread", U.S. Department of Commerce, NBSIR 83-2718, 1983.

24. Cooper, L.Y., Harkleroad, M., Quintiere, J. and Rinkinen, W., "An Experimental Study of Upper Hot Layer Stratification in Full Scale Multiroom Fire Scenarios", ASME 81-HT-9, 1981. Same title in J., of Heat Transfer, November 1982, V. 104, pp. 741-749.

25. Richards, R. and A. Datta, "Ships Lounge Burnout Experiments", U.S. Coast Guard, CG-D-17-82, 1982.

26. Jones, W. and J. Quintiere, "Prediction of Corridor Smoke Filling by Zone Models", Combustion Science and Technology, V. 35, 1984, pp. 239-253.

27. Cooper, L.Y., "The Development of Hazardous Conditions in Enclosures with Growing Fires", Combustion Science and Technology, V. 33, 279-297, 1983.

28. Quintiere, J. and K. Den Braven, "Some Theoretical Aspects of Fire Induced Flows Through Doorways in a Room-Cooridor Scale Model", U.S. Department of Commerce, NBSIR 78-1512, 1978.

29. Zukowski, E.E., Kubota, T., and Lim, C.S., "Experimental Study of Environment and Heat Transfer in a Room Fire. Mixing in Doorway Flows and Entrainment in Fire Plumes", NBS-GCR-85-493, 1985.

30. Jones, Walter, "A Review of Compartment Fire Models", U.S. Department of Commerce, NBSIR 83-2684, 1983.

31. Baum, Howard R. and Rehm, Ronald G., "Calculations of Three Dimensional Buoyant Plumes in Enclosures", Combustion Science and Technology, V. 40, 1984, pp. 55-77.

32. Alvares, N.J., Foote, K.L., and Pagni, P.J., "Forced Ventilated Enclosure Fires", Combustion Science and Technology, V. 39, 1984, pp. 55-81.

33. Cooper, Leonard Y., "On the Significance of a Wall Effect in Enclosures with Growing Fires", Combustion Science and Technology, V. 40, 1984, pp. 19-39.

34. Alpert, R.L., "Turbulent Ceiling-Jet Induced By Large-Scale Fires", Combustion Science and Technology, V. 11, 1985, pp. 197-213.

35. Yang, K.T., Lloyd, J.R., Kanury, A.M., and Satoh, K., "Modeling of Turbulent Buoyant Flows in Aircraft Cabins", Combustion Science and Technology, V. 39, 1984, pp. 107-118.

36. Gross, D., "A Review of Measurements, Calculations and Specifications of Air Leakage Through Interior Door Assemblies", Building Standards, March-April 1981, VL:2, pp. 11-16.

37. Mitter, H.E., "Comparison of Several Compartment Fire Models". An Interim Report, U.S. Department of Commerce, NBSIR 85-3233, 1985.

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